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Review

Radiative cooling surfaces: principles, performance evaluation and applications

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ABSTRACT

With the crisis of greenhouse gases resulting in global warming, radiative cooling can assuage the need to keep cool without any adverse footprints. Radiative cooling is a heat transfer phenomenon in which entities dissipate heat directly into deep space without any effort or requiring input energy. It has been a well-known worldwide phenomenon for nocturnal heat transfer to dissipate heat into deep space. In recent years, however, its potential for cooling during the day leads to be considered as a possible method to mitigate the energy shortage, and it also can benefit the entire world's environment. Radiative cooling materials have leaped with the rapid advancement of nanotechnology. In this review paper, radiative cooling is comprehensively represented with regard to the principle of radiative cooling, energy balance, optimization, and various applications. In the first section, the basic principle of heat transfer mechanisms, which engage simultaneously in radiative cooling surface (RCS), are considered and elaborated. Then various approaches were surveyed to improve the performance of radiative cooling surfaces to outline possible pathways of its development in terms of cooling performance and commercial application. And finally, the application of RCS is discussed to explain the benefits of employing them. This review also makes it possible to researchers to develop the RCS for further upgrade, and the prospect of this subject reviews the major features in summary for further future studies.

1. Introduction

Cooling is an inseparable part of our daily lives in every matter. Air conditioning provides comfort to our lives, and fridges make it possible for us to preserve food for a longer time. According to the US Department of Energy's report, air conditioning utilities are estimated to consume 15% of each house in the USA [1]. Air conditioning facilities, which are conventionally in use, cause environmental concerns and increase the adverse effects of greenhouse gases. So, employing renewable energy and boosting the efficiency of such utility results in reducing the emission of greenhouse gases, and less heat would be dissipated in the atmosphere. In the ancient era, around 2000 years ago, Persians and Indians used the radiative cooling technique to make ice in shallow basins during the night while the ambient temperature was higher than the freezing point, then keep them in ice-house storage in the form of ice piles [2]. In the 20th century, several attempts were made to ameliorate the selective infrared emitters to increase the radiative cooling power during the night [3,4], and many studies have been done to develop radiative cooling surfaces, which is a promising point for the future. In 1978, a sub-ambient temperature material was generated which was able to dissipate heat 24 hours a day, even under sunlight [5]. Therefore, the diurnal radiative cooling surface should have a low absorptance to mitigate the effects of solar radiation. With the advancement in nanotechnology, the diurnal RCS has made significant progress by drawing academic society's attention [6]. Radiative cooling does not require input energy to perform, and it simply emits heat from the earth's surface of approximately 300 K into the depths of the Universe of roughly 3 K. Therefore, the temperature difference between the galaxy and the earth's surface is considerable and can be employed to cool down the surface of the object during the day [8-14]. The invaluable feature of RCS is that they require no input energy to reduce the temperature and cool down so this can directly deduct energy consumption [15,16]. Considering the atmosphere compound, it can be found that the atmosphere has high transparency with 8 μm to 13 μm (Figure 1). For nocturnal radiative cooling, this band needs to be considered. The radiative cooling process is a much more arduous task during the day than during the night since solar radiation attempts to provide positive net cooling. To preclude sunlight heat absorption, the surface requires a massive reflectance in the solar radiation spectrum which is from 300 nm (ultraviolet) to 2,500 nm(near-infrared). Heat

dissipation from the earth's surface through deep space is significantly large enough to keep the surface temperature below ambient even under direct sunlight.

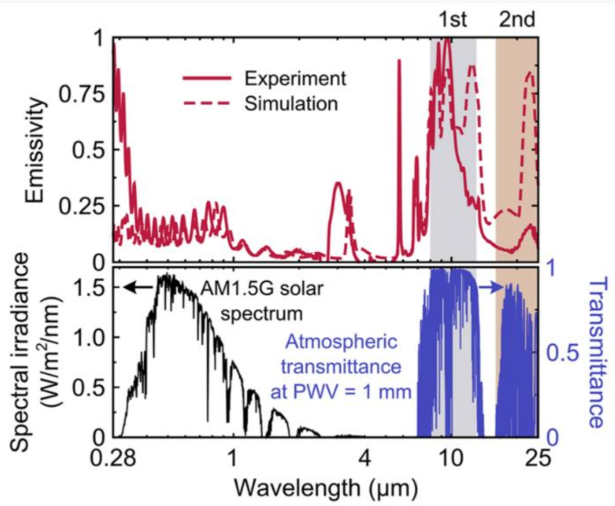

Figure 1. The spectral emissivity of different devices was simulated numerically and measured experimentally. The 1st and 2nd zones indicate the wavelengths of 8 ~ 13 μm and 16 ~ 25 μm of atmospheric windows, respectively [7]

Radiative cooling materials have experienced gradual growth since 2000, and can be classified into four main classes: dielectric multilayers [17-20] organic-inorganic composites [21-23], porous polymers [24-26], and metamaterials [27-30]. Polymers and dielectric materials have high emittance due to their low innate absorptance. Therefore, full solar radiation reflectance is crucial for getting radiative cooling. This review discusses the principles of radiative cooling, sums up novel advancements of radiative cooling, and represents various types of its applications. Meanwhile, we also propose scopes for further developments.

2. Fundamental of radiative cooling

Based on Kirchhoff's law, every object which has an above temperature of 0 K perpetually absorbs and emits electromagnetic waves, which make heat flow exchange between objects (Figure 2). The earth itself is in heat exchange with the dept of space which makes it cooler during the night. If the surface absorption is lower than its emittance, the desired radiative cooling surface is cooler than its ambient even during the day under direct sunlight, and that is the principle of radiative cooling.

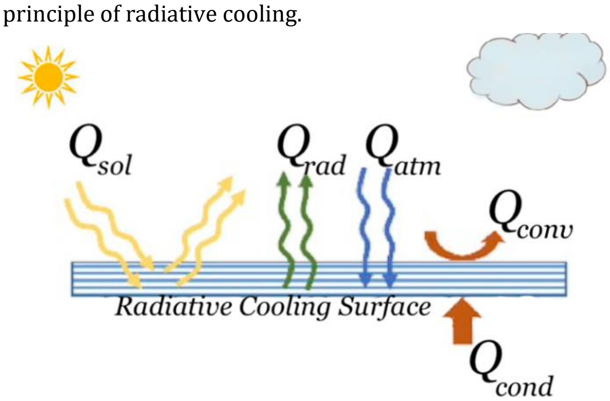

Figure 2. Heat transfer mechanisms of an RCS

2.1 Solar reflectance and surface thermal emittance

Solar reflectance and surface thermal emittance are the two main factors should be considered in RCS design. Since in the solar spectrum from 0.3 μm to 2.5 μm the reflectance must be 100 percent and 0 percent absorption. And consider the atmosphere as an open window that has transmissivity between 8 μm and 13 μm. So, the emittance, in this range, should be 100 percent to transmit heat to deep space, and also in the range of 2.5 μm to 8 μm and higher than 13 μm wavelengths the ideal emittance should be 0 percent since it precludes undesired overheating due to atmospheric irradiation at a high temperature.

2.2 Radiative cooling heat flow

During the day, the net cooling heat flow per unit surface area can be calculated from the:

$$Q_{net} = Q_{rad}(T_{sur}) - Q_{sol} - Q_{atm}(T_{amb}) - Q_{conv} - Q_{cond} \quad (1)$$

Where:

Q_{rad} is the thermal radiation from the RCS, Wm⁻²;

Q_{sol} is the absorbed solar radiation by RCS, Wm⁻²;

$Q_{atm}$is the absorbed atmospheric inward longwave radiation, Wm⁻²;

Q_{conv} and $Q_{cond}$are the convection and conduction heat transfers between the surface and the ambient and in contact surface, Wm⁻².

$Q_{rad,}$ emitted thermal radiation flux from the radiative cooling surface can be achieved as:

$$Q_{rad}(T_{sur}) = A \int cos\theta d\Omega \int_0^{\infty} I_{bb}(\lambda, T_{sur})\varepsilon_{sur}(\lambda, \Omega)d\lambda \quad (2)$$

Where T_{sur} is the RCS temperature, A is the area of RCS, $I_{bb}(\lambda, T_{sur})$is the blackbody's spectral radiation at the temperature T_{sur} in Plank's law; $\int d\Omega = \int_0^{\pi/2} \sin\theta d\theta d\varphi$ is the angular integral over a hemisphere, and ε_{sur} is the RCS radiance vs direction and wavelength; θ, Ω, φ are zenith angle(the angle between the direction of solar radiation incidence and the direction perpendicular to the surface), solid angle, and azimuth angle, respectively; λ indicates wavelength.

$$I_{bb}(\lambda, T_{sur}) = \frac{2hc^2}{\lambda^5}\left[\frac{1}{exp\left(\frac{hc}{\lambda kT}\right)-1}\right] \quad (3)$$

Here, h, k, and c are Planck's and Boltzmann's constants, and the speed of light in a vacuum, respectively. Deep space temperature is as low as 3 K and can absorb Q_{rad} like a blackbody, so its emittance is negligible.

Q_{atm} the absorbed atmospheric radiation by the surface under the clear and cloudless sky can be calculated from:

$$Q_{atm} = A \int cos\theta d\Omega \int_0^{\infty} \varepsilon_{sur}(\lambda, \Omega)\, \varepsilon_{atm}(\lambda, \Omega) I_{bb}(\lambda, T_{amb})d\lambda \quad (4)$$

$\varepsilon_{atm}(\lambda, \Omega)$ is the spectral emissivity of the atmosphere and can be calculated from:

$$\varepsilon_{atm}(\lambda, \Omega) = 1 - t(\lambda)^{1/cos\theta} \quad (5)$$

$t(\lambda)$ is the atmospheric transmittance in the zenith angle and $I_{bb}(\lambda, T_{atm})$ is the blackbody spectral radiation intensity at T_{amb} where T_{amb} is the ambient temperature. The absorbed solar intensity by the cooling surface is indicated as:

$$Q_{sol} = A \int_{0.3}^{2.5} \varepsilon(\lambda, \theta_{sol}) I_{sol}(\lambda)d\lambda \quad (6)$$

$\varepsilon(\lambda, \theta_{sol})$ is the emittance and the $I_{sol}(\lambda)$ is the direct spectral solar irradiation.

Q_{conv} is the convection heat transfer from the surface to the surrounding environment, and h is the convection heat transfer coefficient, Wm^{-2}K^{-1}:

$$Q_{conv} = hA(T_{amb} - T_{sur}) \quad (7)$$

$$Q_{cond} = kA(T_{obj} - T_{sur}) \quad (8)$$

Where Q_{cond} is the conduction heat transfer, k is the conduction coefficient, and T_{obj} is the temperature of the object which is in contact with the RCS. The measurement gadgets and local meteorological parameters are critical factors in determining h. Wind speed is the most crucial parameter since, most of the time, for h determination, a clear sky is selected.

3. Optimization of RCS performance

According to Eq (1), the radiative cooling power can be determined by five main features, which are $Q_{rad}(T_{sur})$, Q_{sol}, $Q_{atm}(T_{amb})$, Q_{conv}, Q_{cond} and discussed in section 1. Here, the purpose is to maximize the $Q_{rad}(T_{sur})$, and minimize the effects of undesired Q_{conv}, Q_{cond} into the RCS. So, a blackbody can be a perfect choice for radiative cooling since through all spectrums it can be a spotless emitter. So far, most compounds that are proposed for improving the radiative cooling function are white in color. The white color exclusively restricts the design in the matter of aesthetic aspects. A metal-dielectric metal (MDM) colored radiative cooler structure is considered to determine the effect of structural factors on radiative cooling performance efficiency and color appearance and reveal the critical parameters [31]. Based on the experiment in ref [32] the straight solar radiation into the surface is about 1000 W/m^{2,} whereas the surface radiation emission is about 70 W/m^2. Therefore, solar radiation dominates there; however, some research on shades is used to block direct sunlight and improve the performance of cooling. Many efforts have been made to create single-layer paints to succeed in radiative cooling during the day; however, most are in need of a thick layer coating or not satisfying the whole-day radiative cooling. In recent work, both $BaSO_4$ paints and $BaSO_4$ nanoparticle films are considered, and the results show a significant whole-day radiative cooling performance. $BaSO_4$ features are low sunlight absorptance since it has a high electron bandgap and phonon resonance at 9 µm for high sky window emissivity [33]. Then one $BaSO_4$ acrylic-based paint indicates a standard digit of competence of 0.77, providing usage simplicity, comfortable paint form, compatibility with commercial paint manufacturing methods, and excellent reliability while it is one of the highest radiative cooling solutions among all [34].

3.1 Impact of local meteorological parameters

Transparency of the sky is one of the most crucial factors to consider in the radiative cooling power of the surface since it is directly connected with the galaxy through the atmospheric window, so it is highly sensitive to air humidity and cloud thickness. Therefore, weather conditions can have a significant impact on the emittance of the RCS. In recent work, the significant effect of wind cover on cooling is indicated both experimentally and theoretically, which illustrates in regions with both humidity and high temperature, the gradient of temperature during the day is roughly 2.3 K, and it is even more during the night [35].

3.2 Gadget design for experiments

It is an absolute need to measure the performance of the radiative cooling surface. Two main features Q_{net} and T_{low} should be measured meticulously in order to rate its efficiency. Q_{net} is the net cooling power of an RCS and T_{st} is the lowest possible steady-state temperature of the RCS that can be reached at $Q_{net} = 0$. Various radiative cooling systems are proposed by many researchers, in the following, some of them are summed up in terms of performance. In order to drop the heat loss, a photonic crystal board which is surrounded by an air chamber, was made and placed at 30° tilt angle to directly expose to sun lights [36].

3.3 Heat losses

Most of the time, the unwilling heat loss in RCS is caused by convection, conduction, and the inferior surrounding radiation that, in a detailed calculation, should be considered. Thermal management approaches should be considered to mitigate the effect of heat loss since they can significantly preclude the reduction of radiative cooling power. A simple example to clarify this is when an RCS is on low-conducting-heat boards, the temperature of the RCS is likely to be lower than ambient, and it definitely works much better than when it is on high-conducting-heat boards. Also, when the RCS is exposed to airflow during the hot days of the year, convection heat transfer plays a significant role in increasing the temperature of the RCS because the RCS will encounter a heat flow on its surface which heats the RCS.

4. Practical application of RCS

In recent years, with the advancement of Nanotechnology and smart materials, radiative cooling materials have become more practical in various cooling applications in multiple devices and systems, such as air conditioning, buildings thermal management, automotive thermal management, and even radiative cooling textiles for personal comfort. More unique applications are surveyed as follows.

4.1 Atmospheric water harvesting

Atmospheric water harvesting is a state-of-the-art method to turn the available moisture in the atmosphere into potable water. Since water vapor is ubiquitous, even in arid areas that suffer from water shortage, it can be a crucial option to access water drawn so much attention in recent years. In ref [37], the feasibility of dew reserving for atmospheric water harvesting is studied which has considered pigmented polymer foil, which is a mixture of TiO_2 and $BaSO_4$ particles or a novel SiO_2/TiO_2 composite, as a radiator with high natural emittance and high solar reflectance. A system is designed to incorporate radiative shielding and radiative cooling in which it dissipates the condensation heat into deep space. In that system, a condenser with a superhydrophobic surface is employed to accumulate water [38].

4.2 Water desalination

Water desalination is a worthy method to remove salt from brackish sources to make fresh water. Conventional methods of salt removal from saline sources, such as thermal desalination and membrane techniques, are in need of energy consumption which increases the cost of water production. Conversely, solar desalination does not require energy to perform however its function is circumscribed to water conditions. In a recent study, a freezing method is proposed for a phase change in water desalination in which a passive radiative cooling method is used to function as a heat sink to

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dissipate heat into the depth of space. It is illustrated in the experiment that after two stages of the radiative cooling-freezing process of the passive desalination, 37.3 g/L saline water to 1.8 g/L with 50 percent attainment and 17.7 g/L saline water to 0.7 g/L attainment. A lattice Boltzmann method, in a recent study, was developed to address the momentum and energy equations and paired with the finite difference discretization of the species transport equation for the concentration of salt. It indicates that the top and left cold surfaces improve the efficiency of desalination twice as the other surfaces. It also revealed that the lower the temperature of the cold wall, the higher the efficiency of condensation [39].

4.3 Solar cell cooling

Solar energy generation, such as Photovoltaics (PV) systems and solar collectors one of the best options to satisfy energy shortages. Conventional solar modules available in the market have an efficiency of roughly 20 percent because their performance suffers from operating overheating under solar irradiance; therefore, their performance can be improved significantly [40]. Normally one sun solar module is able to work at 20 to 40 °C higher than the ambient temperature. Solar modules can be equipped with radiative cooling in order to improve their reliability and performance as their operating temperature decreases [41,42]. A general approach to cool down solar cells with the radiative cooling concept is proposed in ref [43]; as an example, a bare crystalline silicon solar cell is considered, and while its absorption is maintained, it can passively cool down by 18.3 K (Figure 3 and Figure 4).

4.4 Transparent glass

Glass is the most worldwide in used material for transparent envelopments, and objects which have transparent coverages, such as vehicles and buildings, consume massive amounts of energy to cool down in regions with warm weather conditions. In a recent study, a semi-transparent radiative cooling glass employing the adoptive use of solar energy and passive radiative cooling is offered. Experimental tests have been done to compare two small-scale chambers, one with a semi-transparent radiative cooling glass and one with regular glass, which indicates that the chamber equipped with a semi-transparent radiative cooling glass has a lower interior air temperature and the temperature difference can reach 16.4 °C [46]. In the ref [47] a double-mode glazing panel is proposed, which is able to alter the amount of its reflectance (17 percent vs 89 percent) using a silver film on a clear glass of glazing. On cold days transparency let 70 percent of sunshine pass through and only absorbs 13 percent, while on warm days, the silver glazing works as radiative cooling and provides cooling with the power of 20 W/m^2 to 60 W/m^2 [48].

4.5 Buildings thermal management

HVAC systems of buildings utilize 15% of the entire energy in the USA, and decreasing energy consumption and carbon footprint can be a great achievement. Many proposed approaches are not universal and are only able to decrease buildings' energy consumption in some weather conditions and regions. A beneficial method for thermal management and providing comfort in buildings is roof ponds which radiate during the night (Figure 5). Various outlines utilize radiators with a flat plate that circulates water during the night to cool down. In a study, an analytical model developed for the heating purpose was tuned with several radiative cooling equipment (Figure 6). Various operating regimes have been considered, and the experimental data collected from three kinds of radiators examined verified the model's precision. This model is able to predict the outgo temperatures considering the design features of specific radiators, the environmental conditions, and the pattern of the operating system [49]. A bi-functional system equipped with electrostatically-controlled thermal contact conductance is proposed achieving up to 71.6 W/m^2 of chilling power and up to 643.4 W/m^2 of thermal power (over 93% of solar energy utilized) [50].

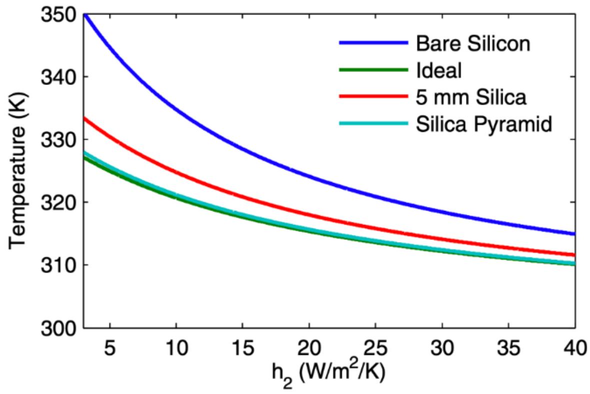

Figure 3. The temperature of PV cells with various emission surfaces' design [44]

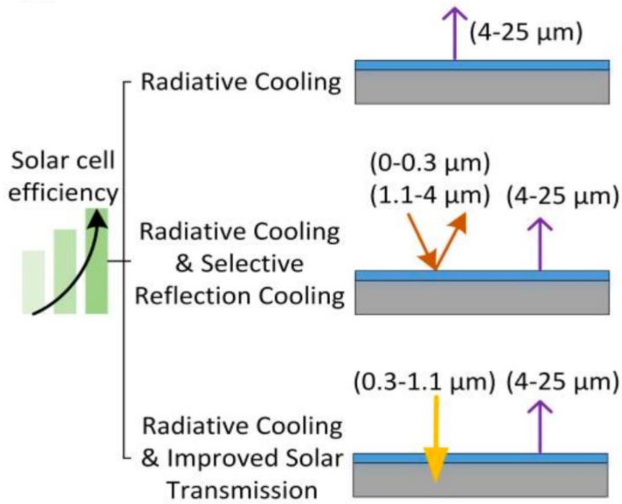

Figure 4. Solar cells' efficiency in various types of radiative cooling studies [45]

4.6 Automotive thermal management

Parking under direct sunlight causes the car interior to overheat and a massive amount of energy must be consumed to cool it down. A new kind of car coverage is proposed to keep the inside temperature low when the car is parked under sunlight. An innovative meta-material coating is used as a layer reflecting sunlight and effectively emitting infrared radiation in the spectrum of the atmospheric window 8 μm to 13 μm. Not only does R coverage provide comfort to the passenger but it also reduces gas consumption and carbon dioxide emission [53]. In a study, a dual-layer film is made for diurnal radiative cooling that included a layer of polymethyl methacrylate (PMMA) monotonously blended with improved silica nanoparticles (SiO_2 NPs) and a layer of silver. The dispersion of the improved SiO_2 NPs in PMMA was improved significantly via in-site grafting PMMA resulting in high

transparency of the radiative cooling film even at a high filling fraction of SiO_2 [54].

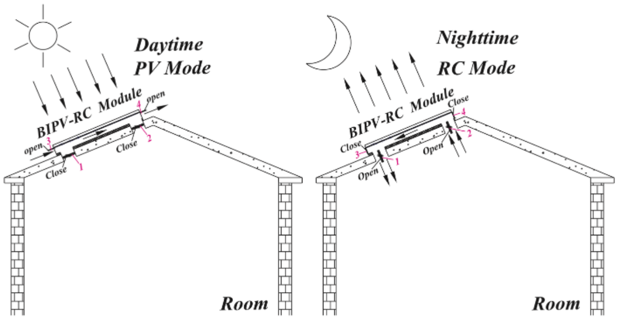

Figure 5. A building-integrated photovoltaic–radiative cooling system [51]

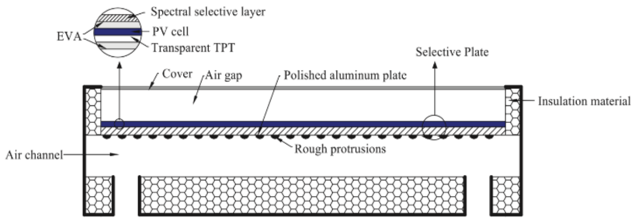

Figure 6. Cross-section of a building-integrated photovoltaic-radiative cooling system [52]

4.7 Radiative cooling textiles for personal comfort

Personal thermal management (PTM) methods focus on textiles to provide personal comfort, either heating or cooling, instead of the entire room's HVAC. Since a huge amount of energy is consumed to provide comfortable temperatures for humans, many research efforts are conducting to develop passive radiative cooling techniques to cool down the human body without consuming energy [55-63]. However, many textiles have been proposed for cooling purposes, and textile to keep the surface temperature lower than ambient during the day has not fully succeeded [64-67]. A worldwide famous natural fabric produced by caterpillars is silk which is shiny and so body-skin friendly [68-71]. New research revealed that silk could be a promising point for achieving radiative cooling during the day due to its hierarchical microstructure [72-75]. A great natural barrier that precludes silk from succeeding radiative cooling under sunlight is its intrinsic feature which is absorption in the ultraviolet spectrum. In a recent study, the nano processing of silk through a molecular bonding design and scalable coupling reagent-assisted dip-coating method is explored and shown that nano processes silk is able to gain lower temperature ambient radiative cooling during the day [76]. In ref [77], it is mentioned that employing novel radiative cooling/heating textiles could drop roughly 40 percent of buildings' energy consumption.

5. Conclusion

In summary, we explained the fundamentals of radiative cooling, which has great cooling potential through the atmospheric window (8 to 13 μm). A precise material selection with accurate nanophotonic arrangements is a crucial factor in improving the cooling performance. Many performance efficiencies in energy systems require sub-ambient radiative cooling surface compounds, and it is indeed both a promising point and a challenge for future research. Radiative cooling materials are still in need of research and development efforts to materialize and commercialize. The application of radiative cooling in buildings, the automotive industry, PV systems, the textile industry, etc., not only able to lower energy consumption but also provides comfort.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The author declares no potential conflict of interest.

References

[1] Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review of buildings' energy consumption information. Energ. Buildings 40, 394–398.

[2] Zeyghami M, Goswami DY, Stefanakos E. A review of clear sky radiative cooling developments and applications in renewable power systems and passive building cooling. Sol Energy Mater Sol Cells. 2018;178(178):115-128. doi:10.1016/j.solmat.2018.01.015

[3] Granqvist CG. Radiative heating and cooling with spectrally selective surfaces. Appl Opt. 1981;20(15):2606-2615. doi:10. 1364/ao.20.002606

[4] Catalanotti, S., Cuomo, V., Piro, G., Ruggi, D., Silvestrini, V., Troise, G., 1975. The radia- tive cooling of selective surfaces. Sol. Energy 17, 83–89.

[5] Harrison, A.W., Walto, M.R., 1978. Radiative cooling of TiO2 white paint. Sol. Energy 20, 185–188.

[6] Sun, X., Sun, Y., Zhou, Z., Alam, M.A., Bermel, P., 2017. Radiative sky cooling: fundamental physics, materials, structures, and applications. Nanophotonics 6, 997–1015.

[7] Suichi, T., Ishikawa, A., Hayashi, Y., & Tsuruta, K. (2018). Performance limit of daytime radiative cooling in warm humid environment. AIP Advances, 8(5), 055124.

[8] Zhao, B., Hu, M., Ao, X., Xuan, Q., Pei, G., 2020. Spectrally selective approaches for passive cooling of solar cells: a review. Appl. Energ. 262, 114548.

[9] Goldstein, E.A., Raman, A.P., Fan, S., 2017. Sub-ambient non-evaporative fluid cooling with the sky. Nat. Energy 2, 17143.

[10] Sohel Murshed, S.M., Nieto de Castro, C.A., 2017. A critical review of traditional and emerging techniques and fluids for electronics cooling. Renew. Sust. Energ. Rev. 78, 821–833.

[11] Zhao, D., Aili, A., Zhai, Y., Xu, S., Tan, G., Yin, X., Yang, R., 2019a. Radiative sky cooling: fundamental principles, materials, and applications. Appl. Phys. Rev. 6.2 (2019): 021306.

[12] Fixsen, D.J., 2009. The temperature of the cosmic microwave background. The Astrophys. J. 707, 916–920.

[13] Liu, B., Xue, C., Zhong, H., Guo, X., Wang, H., Li, H., Du, M., Huang, M., Wei, C., Song, G., Chang, B., Wang, Z., 2021. Multi-bioinspired self-cleaning energy-free cooling coatings. J. Mater. Chem. A 9, 24276.

[14] Zhong, H., Li, Y., Zhang, P., Gao, S., Liu, B., Wang, Y., Meng, T., Zhou, Y., Hou, H., Xue, C., Zhao, Y., Wang, Z., 2021a. Hierarchically hollow microfibers as a scalable and effective thermal insulating cooler for buildings. ACS Nano 15, 10076–10083.

[15] Yin, X., Yang, R., Tan, G., Fan, S., 2020. Terrestrial radiative cooling: using the cold universe as a renewable and sustainable energy source. Science 370, 786–791.

[16] Li, T., Zhai, Y., He, S., Gan, W., Hu, L., 2019. A radiative cooling structural material. Science 364, 760–763.

[17] Raman, A.P., Anoma, M.A., Zhu, L., Rephaeli, E., Fan, S., 2014. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 515, 540–544.

[18] Shi, Y., Li, W., Raman, A., Fan, S., 2017. Optimization of multilayer optical films with a memetic algorithm and mixed integer programming. ACS Photonics 5, 684–691.

[19] Ma, H., Yao, K., Dou, S., Xiao, M., Dai, M., Wang, L., Zhao, H., Zhao, J., Li, Y., Zhan, Y., 2020. Multilayered SiO2 /Si3 N4 photonic emitter to achieve high-performance all-day radiative cooling. Sol. Energ. Mat. Sol. C. 212, 110584.

[20] Dai, Y., Zhang, Z., Ma, C., 2020. Radiative cooling with multilayered periodic grating under sunlight. Opt. Commun. 475, 126231.

[21] Zhou, L., Song, H., Liang, J., Singer, M., Zhou, M., Stegenburgs, E., Zhang, N., Xu, C., Ng, T., Yu, Z., Ooi, B., Gan, Q., 2019. A polydimethylsiloxane-coated metal structure for all-day radiative cooling. Nat. Sustain. 2, 718–724.

[22] Zhong, S., Yi, L., Zhang, J., Xu, T., Xu, L., Zhang, X., Zuo, T., Cai, Y., 2021b. Self-cleaning and spectrally selective coating on cotton fabric for passive daytime radiative cooling. Chem. Eng. J. 407, 127104.

[23] Lee, D., Go, M., Son, S., Kim, M., Badloe, T., Lee, H., Kim, J.K., Rho, J., 2021. Sub-ambient daytime radiative cooling by silica-coated porous anodic aluminum oxide. Nano Energy 79, 105426.

[24] Son, S., Liu, Y., Chae, D., Lee, H., 2020. Cross-linked porous polymeric coating without a metal-reflective layer for sub-ambient radiative cooling. ACS Appl. Mater. Inter 12, 57832–57839.

[25] Wang, T., Wu, Y., Shi, L., Hu, X., Chen, M., Wu, L., 2021. A structural polymer for highly efficient all-day passive radiative cooling. Nat. Commun. 12, 365.

[26] Xiang, B., Zhang, R., Luo, Y., Zhang, S., Xu, L., Min, H., Tang, S., Meng, X., 2021. 3D porous polymer film with designed pore architecture and auto-deposited SiO2 for highly efficient passive radiative cooling. Nano Energy 81, 105600.

[27] Shi, N.N., Tsai, C.C., Camino, F., Bernard, G.D., Yu, N., Wehner, R., 2015. Keeping cool: enhanced optical reflection and radiative heat dissipation in saharan silver ants. Science 349, 298–301.

[28] Lu, Y., Chen, Z., Ai, L., Zhang, X., Zhang, J., Li, J., Wang, W., Tan, R., Dai, N., Song, W., 2017. A universal route to realize radiative cooling and light management in photovoltaic modules. Sol. RRL 1, 1700084.

[29] Zhai, Y., Ma, Y., David, S.N., Zhao, D., Lou, R., Tan, G., Yang, R., Yin, X., 2017. Scalable–manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science 355, 1062–1066.

[30] Zou, C., Ren, G., Hossain, M.M., Nirantar, S., Withayachumnankul, W., Ahmed, T., Bhaskaran, M., Sriram, S., Gu, M., Fumeaux, C., 2017. Metal loaded dielectric resonator metasurfaces for radiative cooling. Adv. Opt. Mater. 5, 1700460.

[31] Xi, W., Liu, Y., Zhao, W., Hu, R., & Luo, X. (2021). Colored radiative cooling: How to balance color display and radiative cooling performance. International Journal of Thermal Sciences, 170, 107172.

[32] Mandal, J., Fu, Y., Overvig, A. C., Jia, M., Sun, K., Shi, N. N., ... & Yang, Y. (2018). Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science, 362(6412), 315-319.

[33] Li, X., Peoples, J., Yao, P., & Ruan, X. (2020). Remarkable Daytime Sub-ambient Radiative Cooling in BaSO4 Nanoparticle Films and Paints. arXiv preprint arXiv:2011.01161.

[34] Li, X., Peoples, J., Yao, P., & Ruan, X. (2021). Ultrawhite BaSO4 paints and films for remarkable daytime subambient radiative cooling. ACS Applied Materials & Interfaces, 13(18), 21733-21739.

[35] Liu, J., Zhang, J., Zhang, D., Jiao, S., Xing, J., Tang, H., ... & Zuo, J. (2020). Sub-ambient radiative cooling with wind cover. Renewable and Sustainable Energy Reviews, 130, 109935.

[36] Raman, A. P., Anoma, M. A., Zhu, L., Rephaeli, E., & Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. Nature, 515(7528), 540-544.

[37] Nilsson, T. M. J., Vargas, W. E., Niklasson, G. A., & Granqvist, C. G. (1994). Condensation of water by radiative cooling. Renewable Energy, 5(1-4), 310-317.

[38] Haechler, I., Park, H., Schnoering, G., Gulich, T., Rohner, M., Tripathy, A., ... & Poulikakos, D. (2021). Exploiting radiative cooling for uninterrupted 24-hour water harvesting from the atmosphere. Science Advances, 7(26), eabf3978.

[39] Mousavi, S. P., Jalali, A., & Rahimian, M. H. (2022). Numerical simulation of indirect freezing desalination using lattice Boltzmann method. Physics of Fluids, 34(7), 073322.

[40] Mohamadkhani, M., Kowsary, F., & Ghasemi, M. (2023). Techno-economic assessment of fixed solar panels and sun-tracking technology in solar farms in the districts of Tehran and Qazvin in Iran. Future Energy, 2(3), 29-37.

[41] Safi TTST, Munday JJN. Improving photovoltaic performance through radiative cooling in both terrestrial and extraterrestrial environments. Opt Express 2015;23:A1120–8.

[42] Sun X, Silverman TJ, Zhou Z, Khan MR, Bermel P, Alam MA. Optics-based approach to thermal management of

photovolta- ics: selective-spectral and radiative cooling. IEEE J Photovolta- ics 2017;7:566–74.
[43] Zhu, L., Raman, A., Wang, K. X., Abou Anoma, M., & Fan, S. (2014). Radiative cooling of solar cells. Optica, 1(1), 32-38.
[44] Zhu, L., Raman, A., Wang, K. X., Abou Anoma, M., & Fan, S. (2014). Radiative cooling of solar cells. Optica, 1(1), 32-38.
[45] Ahmed, S., Li, Z., Javed, M. S., & Ma, T. (2021). A review on the integration of radiative cooling and solar energy harvesting. Materials Today Energy, 21, 100776.
[46] Zhao, B., Wang, C., Hu, M., Ao, X., Liu, J., Xuan, Q., & Pei, G. (2022). Light and thermal management of the semi-transparent radiative cooling glass for buildings. Energy, 238, 121761.
[47] Zhao, X., Aili, A., Zhao, D., Xu, D., Yin, X., & Yang, R. (2022). Dynamic glazing with switchable solar reflectance for radiative cooling and solar heating. Cell Reports Physical Science, 3(4), 100853.
[48] Zhao, X., Aili, A., Zhao, D., Xu, D., Yin, X., & Yang, R. (2022). Dynamic glazing with switchable solar reflectance for radiative cooling and solar heating. Cell Reports Physical Science, 3(4), 100853.
[49] Erell, E., & Etzion, Y. (2000). Radiative cooling of buildings with flat-plate solar collectors. Building and environment, 35(4), 297-305.
[50] Li, X., Sun, B., Sui, C., Nandi, A., Fang, H., Peng, Y., ... & Hsu, P. C. (2020). Integration of daytime radiative cooling and solar heating for year-round energy saving in buildings. Nature communications, 11(1), 1-9.
[51] Zhao, B., Hu, M., Ao, X., & Pei, G. (2017). Conceptual development of a building-integrated photovoltaic–radiative cooling system and preliminary performance analysis in Eastern China. Applied energy, 205, 626-634.
[52] Zhao, B., Hu, M., Ao, X., & Pei, G. (2017). Conceptual development of a building-integrated photovoltaic–radiative cooling system and preliminary performance analysis in Eastern China. Applied energy, 205, 626-634.
[53] Lv, Y., Huang, A., Yang, J., Xu, J., & Yang, R. (2021). Improving cabin thermal environment of parked vehicles under direct sunlight using a daytime radiative cooling cover. Applied Thermal Engineering, 190, 116776.
[54] Lei, M. Q., Hu, Y. F., Song, Y. N., Li, Y., Deng, Y., Liu, K., ... & Li, Z. M. (2021). Transparent radiative cooling films containing poly (methylmethacrylate), silica, and silver. Optical Materials, 122, 111651.
[55] Office of Energy Saver. Heating and Cooling US Department of Energy www.energy.gov/heating-cooling
[56] Rödel, H., Schenk, A., Herzberg, C. & Krzywinski, S. Links between design, pattern development and fabric behaviours for clothes and technical textiles. Int. J. Cloth. Sci. Tech. 13, 217–227 (2001).
[57] Cho, S. C. et al. Surface modification of polyimide films, filter papers, and cotton clothes by HMDSO/toluene plasma at low pressure and its wettability. Curr. Appl. Phys. 9, 1223–1226 (2009).
[58] Parvari, R. A. et al. The effect of fabric type of common Iranian working clothes on the induced cardiac and physiological strain under heat stress. Arch. Environ. Occup. Health 70, 272–278 (2015).
[59] Hsu, P. C. et al. Radiative human body cooling by nanoporous polyethylene textile. Science 353, 1019–1023 (2016).
[60] Peng, Y. et al. Nanoporous polyethylene microfibres for large-scale radiative cooling fabric. Nat. Sustain. 1, 105–112 (2018).
[61] Zhang, X. et al. Dynamic gating of infrared radiation in a textile. Science 363, 619–623 (2019).
[62] Cai, L. et al. Spectrally selective nanocomposite textile for outdoor personal cooling. Adv. Mater. 30, 1802152 (2018).
[63] Hsu, P. C. et al. A dual-mode textile for human body radiative heating and cooling. Sci. Adv. 3, e1700895 (2017).
[64] Raman, A. P., Anoma, M. A., Zhu, L., Rephaeli, E. & Fan, S. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 515, 540–544 (2014).
[65] Zhai, Y. et al. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science 355, 1062–1066 (2017).
[66] Li, T. et al. A radiative cooling structural material. Science 364, 760–763 (2019).
[67] Mandal, J. et al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science 362, 315–319 (2018).
[68] Yang, Y. & Li, S. Silk fabric non-formaldehyde crease-resistant finishing using citric acid. J. Text. Inst. 84, 638–644 (1993).
[69] Gong, R. H. & Mukhopadhyay, S. K. Fabric objective measurement: a comparative study of fabric characteristics. J. Text. Inst. 84, 192–198 (1993).
[70] Huang, F., Wei, Q., Liu, Y., Gao, W. & Huang, Y. Surface functionalization of silk fabric by PTFE sputter coating. J. Mater. Sci. 42, 8025–8028 (2007).
[71] Cai, Z., Jiang, G. & Yang, S. Chemical finishing of silk fabric. Color. Technol. 117, 161–165 (2001).
[72] Shi, N. et al. Keeping cool: enhanced optical reflection and heat dissipation in silver ants. Science 349, 298–301 (2015).
[73] Jin, H. & Kaplan, D. L. Mechanism of silk processing in insects and spiders. Nature 424, 1057–1061 (2003).
[74] Choi, S. et al. Anderson light localization in biological nanostructures of native silk. Nat. Commun. 9, 452 (2018).
[75] Shi, N. et al. Nanostructured fibers as a versatile photonic platform: radiative cooling and waveguiding through transverse Anderson localization. Light Sci. Appl. 7, 37 (2018).
[76] Zhu, B., Li, W., Zhang, Q., Li, D., Liu, X., Wang, Y., ... & Zhu, J. (2021). Subambient daytime radiative cooling textile based on nanoprocessed silk. Nature Nanotechnology, 16(12), 1342-1348.
[77] Ma, Z., Zhao, D., Wang, F., & Yang, R. (2022). A novel thermal comfort and energy saving evaluation model for radiative cooling and heating textiles. Energy and Buildings, 258, 111842.